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Revising and Validating Spectral Irradiance Reference Standards for Photovoltaic Performance

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Daryl R. Myers and Keith Emery
National Renewable Energy Laboratory

Christian Gueymard
Consultant

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National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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REVISING AND VALIDATING SPECTRAL IRRADIANCE REFERENCE STANDARDS FOR PHOTOVOLTAIC PERFORMANCE EVALUATION

Daryl R. Myers
National Renewable Energy Laboratory
1617 Cole Blvd Golden CO 80401
(v) 303-384-6768 (f) 303-384-6391
daryl_myers@nrel.gov

Keith Emery
National Renewable Energy Laboratory
1617 Cole Blvd Golden CO 80401
(v) 303-384-6632 (f) 303-384-6604
keith_emery@nrel.gov

C. Gueymard
Consultant, 174 Bluebird Lane, Bailey, CO
(v) 303-838-1085
cgueymard@mac.com

ABSTRACT

In 1982, the American Society for Testing and Materials (ASTM) adopted consensus standard direct-normal and global-tilted solar terrestrial spectra (ASTM E891/E892). These standard spectra were intended to evaluate photovoltaic (PV) device performance and other solar-related applications. The International Standards Organization (ISO) and International Electrotechnical Commission (IEC) adopted these spectra as spectral standards ISO 9845-1 and IEC 60904-3. Additional information and more accurately representative spectra are needed by today's PV community. Modern terrestrial spectral radiation models, knowledge of atmospheric physics, and measured radiometric quantities are applied to develop new reference spectra for consideration by ASTM.

Keywords: Reference, Standard, Spectrum, Modeling, Models

INTRODUCTION

Fixed reference or standard solar spectra are important components of standard reporting conditions for such spectrally selective devices as PV devices. In 1982, The American Society for Testing and Materials (ASTM see http://www.astm.org/) committee E44 on Solar, Geothermal, and Other Alternative Energy Sources developed the first standard spectra to meet these needs through its subcommittee E44-02 on Environmental Parameters. The committee developed standards for standard reporting conditions [1], calibrating reference cells and modules and evaluating the performance of cells, modules and devices [2].

The committee used then available atmospheric spectral solar transmission models, measured data, and standard atmospheric conditions to produce reference spectra thought to be representative of reasonable natural conditions and PV applications. These spectra (originally ASTM E891-82, for *direct normal spectral irradiance*, and E892-82, for *total hemispherical spectral irradiance on a south facing 37° tilted surface*) were first approved in 1982, based on unpublished communications. In 1987, the spectra were recalculated (resulting in significant changes) based upon published references [3]. These changes were approved by the ASTM ballot process in 1987 and re-approved in 1992 [4, 5]. The E892-87 spectrum was adopted by the International Electrotechnical Commission (IEC), as part of IEC 60904-3 [6]. In 1992, the International Standards Organization (ISO) adopted both E891-92 and E892-92 spectra into a single standard, ISO 9845-1992 [7]. In 1998 the standard spectra were moved to the jurisdiction of ASTM subcommittee G03.09 on Radiometry. That committee editorially (i.e., with no changes in technical content) combined E891-92 and E892-92 into ASTM G159-99 [8] to be consistent with ISO 9845-1. In 1999, ASTM formally withdrew E891 and E892, replacing them with the combined G159-99 standard.

The reference spectra represent terrestrial solar spectral irradiance on a specific surface under one set of specified atmospheric conditions. The direct normal spectrum is the direct component contributing to the total hemispherical radiation on a 37°-tilted surface. The primary reference describing the conditions and parameters entering into the existing standards are the papers by Bird, Hulstrom, and Lewis, 1983 [3,9].

After more than 14 years without modification, technical issues concerning the usefulness and accuracy of the spectra have arisen. These issues suggest updates are needed to meet the greater technical demands of industry and users in the PV, solar energy systems, materials degradation, fenestration, and other areas. In particular, recent work [10-12] has shown that the direct normal reference spectrum is not representative of sunny conditions in regions with high direct normal where concentrator PV systems might be deployed.

NOMENCLATURE

As used in the current ASTM spectral standard G-159, the following definitions are provided here:

Aerosol optical depth (AOD)—(also called "optical thickness" or "turbidity") the wavelength-dependent total extinction (scattering and absorption) by aerosols in the atmosphere. AOD at 500 nanometers (nm) is commonly reported.

Air mass (AM)—Ratio of the mass of the atmosphere in the actual sun-observer path to the mass that would exist if the sun were directly overhead. Relative air mass (AM_R) AM_R is the ratio of the observed path length through the atmosphere to the path length through the atmosphere directly overhead. AM_R varies as secant of the zenith angle, Z. Absolute Air Mass, AM_A, varies with the zenith angle and local barometric pressure, P. Using P_O to indicate standard atmospheric pressure, $AM_A \approx (P/P_O) \sec Z$.

Air mass zero (AM0)—solar radiation quantities outside the Earth's atmosphere at the mean Earth-Sun distance (1 Astronomical Unit). [13]

Circumsolar radiant energy—radiation scattered by the atmosphere from an area of the sky immediately adjacent to the sun, the solar aureole.

Diffuse solar irradiance, diffuse, E_d—downward scattered solar flux received on a horizontal surface from a solid angle of 2π-steradian (hemisphere) with the exception of a conical solid angle with a 100 mrad (approximately 6°) included plane angle centered on the sun's disk.

Direct solar irradiance, direct, E—solar flux coming from the solid angle of the sun's disk on a surface perpendicular to the axis of that solid angle. Also referred to as "direct normal irradiance".

Hemispherical solar irradiance, E_H —the solar radiant flux received from within the 2-π steradian field of view of a given plane from the portion of the sky dome and the foreground included in the plane's field of view, including both diffuse and direct solar radiation. For the special condition of a horizontal plane the hemispherical solar irradiance is properly termed *global solar irradiance, E_G.* The adjective *global* should refer only to hemispherical solar radiation on a horizontal surface.

Integrated irradiance $E_{\lambda_1-\lambda_2}$—spectral irradiance integrated over a specific wavelength interval from λ_1 to λ_2, measured in $W{\bullet}m^{-2}$.

Solar constant—the total solar irradiance at normal incidence on a surface in space (AM0) at the earth's mean distance from the sun. (1 astronomical unit, or AU = 1.496 x 10^{11} m). The current accepted value of the solar constant is 1366.1 Wm^{-2} ± 7 W m^{-2} [13]. The AM0 solar flux at the Earth varies by ±3% about the solar constant as the earth-sun distance varies through the year, and with the solar sunspot activity[*].

Spectral solar irradiance, E_λ—solar irradiance E per unit wavelength interval at a given wavelength λ (unit: Watts per square meter per nanometer, $W{\bullet}m^{-2}{\bullet}nm^{-1}$)

Spectral passband— the effective wavelength interval within which spectral irradiance is considered to pass, as through a filter or monochromator. The convolution integral of the *spectral passband* (normalized to unity at maximum) and the incident spectral irradiance produces the effective transmitted irradiance. Spectral passband may also be referred to as the *spectral bandwidth* of a filter or device. Passbands are specified as the interval between wavelengths at which one half of the maximum transmission of the filter or device occurs, or as *full-width at half-maximum*, FWHM.

Spectral interval—the distance in wavelength units between adjacent spectral irradiance data points.

Spectral resolution—the minimum wavelength difference between two wavelengths that can be unambiguously identified.

Total precipitable water—depth of a column of water with a section of 1 cm^2 equivalent to the condensed water vapor in a vertical column from the ground to the top of the atmosphere. (Unit: atmosphere-cm or g/cm^2)

Total ozone— depth of a column of ozone equivalent to the total of the ozone in a vertical column from the ground to the top of the atmosphere. (Unit: atmosphere-cm)

Total nitrogen dioxide— depth of a column of pure nitrogen dioxide (NO_2) equivalent to the total of the NO_2 in a vertical column from the ground to the top of the atmosphere. (Unit: atmosphere-cm)

Wavenumber— a unit of frequency, ν, in units of reciprocal centimeters (symbol cm^{-1}) commonly used in place of wavelength, λ. The relationship between wavelength and frequency is defined by $\lambda \nu = c$, where c is the speed of light in vacuum. To convert wavenumber to nanometers, λ nm = 1 ? $10^7/\nu\ cm^{-1}$

DESCRIPTION OF PRESENT STANDARD SPECTRA

The present reference spectra described in ASTM G-159 were derived in the early 1980's. A Monte Carlo spectral radiative transfer model, BRITE, [14] was used in conjunction with the AM0 spectrum of Wehrli, [15], the United States Standard Atmosphere (USSA) of 1976 [16] and atmospheric aerosol profiles of Shettle [17]. Note the USSA contains no information concerning atmospheric aerosol properties.

The geometric conditions selected were considered reasonable averages [1] for flat plate PV modules deployed in the 48 contiguous states of the United States of America (U.S.). The receiving surface is defined as an inclined plane tilted at 37° from the horizontal toward the equator, facing south (azimuth of 180°). The only specification of the solar position is that the air mass (AM) is equal to 1.5, for an observer at sea level, with no corrections for atmospheric refraction. At AM=1.5, the zenith angle for the sun is 48.19° and the elevation angle is 41.81° above the horizon. This geometry is shown in Figure 1.

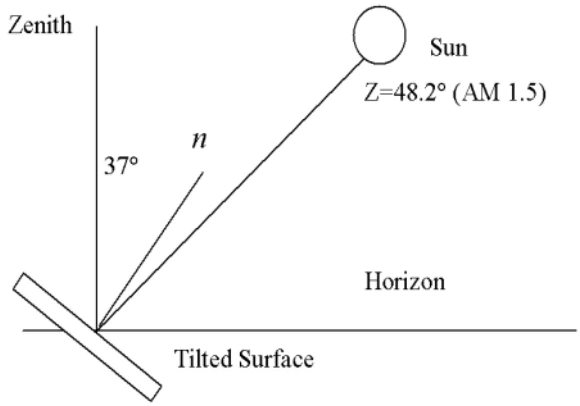

Figure 1. Solar geometry for reference spectral distributions. The solar azimuth is 180°, in the same plane as the normal to the "south facing" (in the northern hemisphere) surface tilted toward the equator. Normal to the tilted plane is *n*.

The AM 1.5 condition was selected based work performed at the Jet Propulsion Laboratory by Gonzalez and Ross [18] showing that approximately 50% of solar radiation resources for energy production by photovoltaic conversions systems occurred above and below AM1.5.

Atmospheric conditions specified in ASTM G159-99 are summarized as follows:

a) The 1976 U.S. Standard Atmosphere (USSA) profiles of temperature, pressure, air density, and molecular species density specified in 33 layers starting from sea level [16] is the atmosphere model used.
b) An absolute air mass of 1.5 (solar zenith angle 48.19°) at sea level.
c) An aerosol optical depth, AOD, or "turbidity" of 0.27 at 500 nm, said to "correspond to a sea-level meteorological range of 23 km" was chosen, based on the 1978 work of Shettle and Fenn [17].
d) A constant surface albedo (reflectivity) of 0.2 assuming the surface has a Lambertian reflectivity.
e) Total precipitable water vapor content = 1.42 cm
f) Total Ozone content = 0.34 atm-cm

Water vapor and Ozone content of the USSA atmosphere were derived by integrating the 33 layers to produce the total equivalent amounts of these constituents.

Using the above prescribed geometry and atmospheric conditions in conjunction with the AM0 spectrum of Wehrli and a Monte Carlo radiative transfer code, direct normal and total hemispherical spectral irradiance were generated, resulting in the spectral distributions shown in Figure 2.

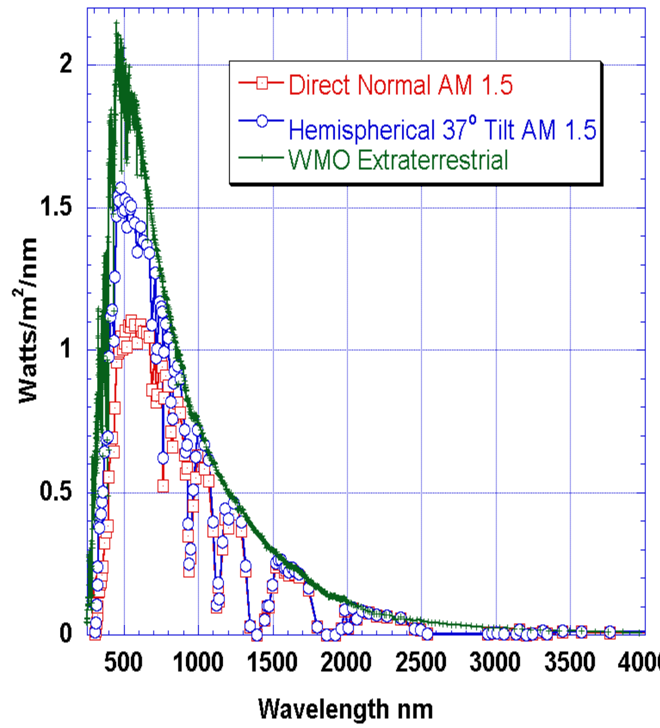

Figure 2. World Meteorological Organization (WMO) Wehrli extraterrestrial (ETR) spectrum and ASTM G159 direct and Hemispherical, 37° south facing tilted surface spectra tabulated in the current standard.

The integrated total irradiance for the ASTM G159 direct normal and hemispherical spectra are 767 W/m² and 967 W/m², respectively. To achieve a "standard reporting condition" irradiance of 1000 W/ m², the hemispherical tilted spectrum was simply scaled by multiplying by the ratio of 1000/967, or 1.034. The curve for hemispherical tilt spectrum in Figure 2 is for the un-normalized hemispherical spectrum.

EVALUATION OF PRESENT STANDARD SPECTRA

Many different combinations of atmospheric conditions can be selected to provide a reference spectrum. However, defining an "appropriate" combination of both hemispherical and direct normal spectra (of great importance when evaluating the performance concentrating PV systems) is a challenge.

It is not possible to explicitly re-generate the existing G159 spectra using the original software tools and input files used by Bird, Hulstrom, and Lewis in 1982-1985. The BRITE computer code used to generate the reference spectra used seven binary coded data tapes for a Control Data Corporation CDC 6600 mainframe computer. Attempts to convert and validate the binary input data tapes, and the BRITE code, to be compatible with minicomputers were unsuccessful due to limited resources.

Broadband and Meteorological Conditions

Table 1 summarizes the irradiance and meteorological conditions stated in *Standard Reporting Conditions* (SRC), or *Standard Test Conditions* (STC) used in the photovoltaic community. The last row summarizes data for the western U.S. from the United States National Solar Radiation Data Base (NSRDB) [19] as reported elsewhere [10-12].

Table 1. Summary of standard conditions. HNI and DNI denote hemispherical normal and direct normal broadband irradiance, respectively, on a solar-tracking surface.

Standard Name Citation	Irradiance W/m² Spectrum	Temp.	Wind Speed	Comments
STC or SRC [1, 8]	Hemi-spherical AM1.5 Spectrum	25°C cell	N/A	Often measured using solar simulators; Peak output
PVUSA Test Conditions [20]	1000 Hemi-spherical 850 DNI No spectral reference	20°C ambient	1 m/s 10 m height	Outdoor Test; Peak Output (utilities)
Nominal operating conditions (NOCT) [1]	800 Hemi-spherical No spectral reference	20°C ambient	1 m/s module height	Nominal operating cell temperature
"Ad hoc " DNI [21, 22]	1000 DNI AM 1.5 DNI Spectrum	20 °C Device	N/A	DNI spectrum Scaled by 1.3
Mean Prevailing [10-12]	HNI= 1000 ±10 DNI=836 ±44	23.7 ±8.8°C ambient	4.5 ±2.8 m/s 10 m height	Extracted from NSRDB for HNI indicated

Table 2 compares SRC and Photovoltaic for Utility Scale Applications (PVUSA) Test Conditions (PTC)[20] with the medians of available meteorological and atmospheric parameters when HNI approximates an SRC irradiance level of 1 kW/m² within ±10 W/m² The commonly used values of 850 W/m² for DNI and 20°C for ambient temperature appear appropriate for concentrator testing. A more realistic wind speed should be the more frequently observed 4 m/s. The water vapor and air-mass conditions approximate those defining the ASTM reference spectra. The large difference between the median AOD observed and that used to define the reference direct normal spectra is of importance to the concentrating solar collector community.

Table 2. Average medians of prevailing conditions at 1000 W/m2 ± 10 W/M² irradiance for 37 sites in western United States compared with SRC.

Parameter	Average Median (prevailing)	St. Dev.	SRC	PVUSA Test Conditions
DNI, W/m²	834.4	22.8	-------	850.0
HNI, W/m²	1001.0	1.3	1000	1000
Ambient Temp. °C	24.4	4.0	25*	20
Wind Speed, m/s	4.4	1.1	------	1.0
H_2O, atm-cm	1.4	0.5	1.42	-----
AOD	0.08 &	0.02	0.27+	-----
Air Mass	1.43	0.09	1.50	-----

*Device Temperature & Broadband AOD in the NSRDB is derived by inversion of Beer's law for the broadband DNI and is approximately 60% smaller than the monochromatic AOD at 500 nm at ASTM SRC.+ AOD at 500 nm.

Technologies such as multi-junction III-V PV cells are particularly spectrally sensitive. The difference in efficiency due to using the standard *direct* versus *global* spectrum is known to be on the order of 5% (out of about 30% laboratory efficiency) for such cells [23]. Because of the discrepancy between the *prevailing* versus *reference* AOD conditions, we compared available measured spectra to the reference spectra.

Comparing Measured with Standard Spectral Distributions

We selected spectra from the SERI Solar Spectral Database (SSDB) developed by Riordan et al., [24] to compare with the ASTM G-159 reference spectra. The SSDB contains over 3300 spectra measured in 1987 and 1988. Spectra were measured with Li-Cor model LI-1800 spectrometers. Measurement sites were the Florida Solar Energy Center (FSEC), Cape Canaveral, FL; Pacific Gas and Electric (PG&E), San Ramon, CA; and Denver, CO. Direct-normal measured spectra were selected when the air mass was 1.5 ±0.1. A total of 144 spectra meeting these criteria were available.

The mean DNI irradiance for the FSEC and PG&E spectra were 865 ± 85 W/m², and 883 ± 32 W/m², respectively. Only 4 of the 76 Denver direct-normal spectra in the SSDB met the selection criteria, so we randomly selected 500 clear sky spectra from over 3000 spectra collected at NREL (near Denver) during PV reference cell calibrations [25]. A grand total of 644 spectra were analyzed.

The means of the observed direct normal spectra cluster nearer the hemispherical tilt spectrum than to the direct reference spectrum, as shown in Figure 3. This is primarily because of the high aerosol optical depth (0.27) defining the direct reference spectrum, and generally lower AOD in the measured dataset.

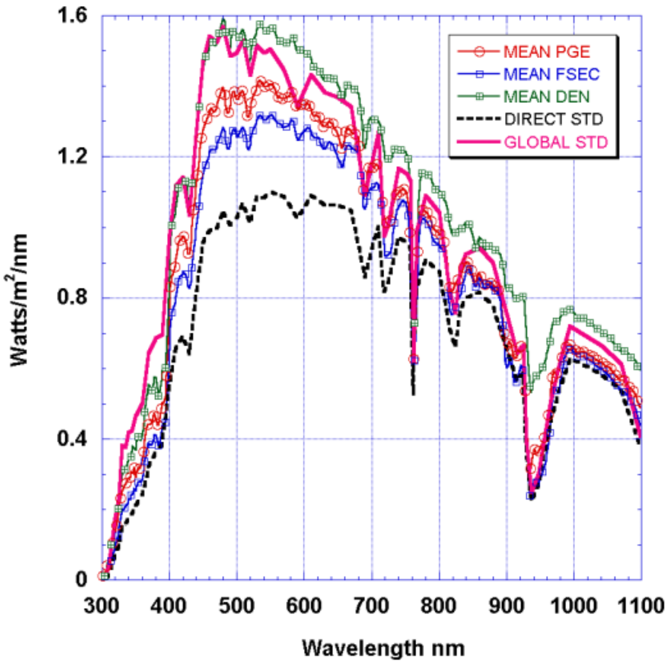

Figure 3. ASTM direct (dash) and tilted hemispherical (line) spectra compared with mean measured FSEC (open square, n=120), PG&E (circle, n=20), and Denver (cross square, n=500) DNI spectra.

The direct normal spectra measured when global normal irradiance is near 1 kW/m^2 and at AM 1.5 are significantly higher in magnitude than the existing direct normal reference spectrum. The mean of the median broadband AOD observed in our analysis of the NSRDB data set (0.08;equivalent to a monochromatic aerosol optical depth at 500 nm of 0.125) is considerably lower than the 0.27 AOD used to generate the G159 spectra. We conclude that direct normal reference spectra for flat-plate and concentrating PV applications do not represent appropriate spectral conditions when prevailing conditions are near standard reporting conditions. We therefore embarked on a program to select an appropriate monochromatic aerosol optical depth and an accurate spectral model to generate spectra to produce a more representative reference combination of hemispherical and direct reference spectra for consideration by ASTM as revised reference spectra.

SPECTRAL ATMOSPHERIC TRANSMISSION MODELS

Atmospheric radiative transfer models have significantly improved in the years since the reference standard spectra were first adopted. Improved parameterization of the absorption properties of the atmosphere's gaseous constituents and modeling of the properties of aerosols in the atmosphere are some of the essential advances made. Models can be classified as simple, moderately complex, and rigorous, depending on the balance between empirical and theoretical principles incorporated into them (see the review in [26]).

Rigorous Models: FASCODE, MODTRAN, LOWTRAN

A high resolution rigorous spectral atmospheric transmission models is the "Fast Atmospheric Spectral Code" or FASCODE, developed by the Air Force Geophysical Laboratory (AFGL) [27-31]. FASCODE is a "line-by-line" (LBL) transmission model, making use of fundamental radiative transfer theory and the quantum mechanical properties of atmospheric constituents. The catalog of absorption lines and their fundamental properties is the "High-resolution Transmission" (HITRAN) molecular absorption database, assembled and maintained by the Harvard Smithsonian Astrophysical Observatory (SAO)[32, 33].

HITRAN is considered an international standard database for atmospheric molecular spectroscopy. HITRAN contains over 1 million spectral absorption lines for 38 gaseous constituents of the earth's atmosphere, along with 27 additional molecules for which absorption cross sections only are given. FASCODE is a radiative transfer model for atmospheric transmission over very narrow (thousandths of nm) bandwidths.

A "moderate resolution transmission" code, MODTRAN, also developed by AFGL, is a very complex, moderate resolution rigorous radiative transfer model. MODTRAN evolved over 30 years from the "low resolution transmission", or LOWTRAN [27] series of atmospheric transmission models. The FORTRAN source code for MODTRAN (version 4) is comprised of about 52,000 lines of code. Both LOWTRAN and MODTRAN are "band model" implementations of the HITRAN database. These are computationally efficient "transmission function" approximations to produce an "equivalent absorption" over a relatively larger passband for use by the radiative transfer code.

The highest computational resolution MODTRAN produces is 1 wavenumber, or 1 cm^{-1}, compared 20 cm^{-1} for the previous LOWTRAN family. The highest effective resolution in the MODTRAN results is quoted as 2 cm^{-1}[34]. Thus, at 250 nm, 500 nm, and 1000 nm MODTRAN resolution is approximately 0.006 nm, 0.025, and 0.100 nm, and LOWTRAN resolution is 0.125 nm, 0.500 nm, and 2.0 nm, respectively

The AFGL has licensed FASCODE, MODTRAN, and LOWTRAN as commercially available products for use on personal computers through the ONTAR Corporation, (http://www.ontar.com). These models require expertise in atmospheric physics and radiative transfer, careful reading of the documentation, and extensive input parameter prescription to produce and interpret meaningful results. While default profiles and parameters are available, the user can prescribe an arbitrary set of parameters (including clouds, fog, rain, smoke, etc.) and geometry for calculating sky and atmospheric radiance or direct beam transmission. These models cannot directly provide the diffuse irradiance incident on a tilted receiver.

Simple Spectral Models: SPCTRL2

Complex, rigorous atmospheric transmission models such as MODTRAN are not appropriate for all applications, such as solar energy system engineering. A simpler parameterized or semi-empirical model can usually meet the user needs. Models have been published in the literature [35-40], based on the transmittance model of Leckner [41]. In particular, the SPCTRL2 model developed by Bird and colleagues at SERI/NREL [35, 42, 43], has been extensively distributed and evaluated [44].

SPCTRL2 relies on the product of empirical, closed-form transmission functions for the most important elements of atmospheric extinction: air molecules, ozone, water vapor, uniformly mixed gases, and aerosols. The product of the transmission functions modifies the extraterrestrial spectral direct beam irradiance to produce direct beam radiation. Simple theoretical relations are used to estimate the distribution of sky and ground reflected radiation. The model produces spectral results for 122 irregularly spaced wavelengths from 300 nm to 4000 nm. The model is implemented in about 120 lines of source code in FORTRAN. The equations are simple enough to be entered in personal computer spreadsheets.

Bird developed the SPCTRL2 model at the same time that he was using BRITE to develop the ASTM reference spectra (1982-1985). Bird used BRITE to validate the SPCTRL2 model, and compared it with several of the other simple models cited above. Most SPCTRL2 model wavelengths are common with the ASTM G159 spectra, but there is not an exact one-to-one correspondence. Because SPCTRL2 and BRITE are different models, they do not produce exactly the same result at a particular wavelength. Thus, SPCTRL2 can only generate an approximation to the reference spectra. [42]

Moderately Complex Model: SMARTS2

To fill the gap between the two previous categories of models, one of the authors, (Gueymard), developed SMARTS2, (Spectral Model for Atmospheric Transmission of Sunshine), which is slightly more complex than SPCTRL2. SMARTS2, version 2.9, is based on new and more accurate parameterizations of the different extinction processes in the atmosphere; including temperature and relative humidity effects [45-47]. More recent absorption coefficients derived from spectroscopic data are included. A revised extraterrestrial spectrum with 2002 wavelengths between 280 nm and 4000 nm is used, based on Bueckner, et al. [48] (280 nm to 412 nm) and Kuruz [49] (412 nm to 4000 nm), along with six other extraterrestrial spectra derived from those available in MODTRAN version 4 (MODTRAN4). The spectral step size of the extraterrestrial spectrum is 0.5 nm from 280 nm to 400 nm, 1 nm from 400 nm to a transitional wavelength at 1702 nm and 5 nm from 1705 nm and thereafter. The effective spectral resolution for SMARTS2 at each computed point is approximately the same 2 cm^{-1} resolution as the complex MODTRAN model results.

There is an ASTM standard extraterrestrial spectrum, E490-00, [11] which is compiled from measurements as well as the same sources mentioned above, including the Kurucz spectrum The three extraterrestrial spectra mentioned here (SMARTS2, E490-00, and Wehrli/WMO) differ from each other only slightly. The largest discrepancies are in the region of 2100 nm to 2400 nm where there are differences (0.014 $W/m^2/nm$ out of a value of approximately 0.05 $W/m^2/nm$) between the older WMO spectrum and the other two. It has been argued that the WMO spectrum was affected by residual water vapor absorption in the near infrared due to incomplete atmospheric corrections from terrestrial measurements (e.g., [50]). The E490 extraterrestrial spectrum includes measured data from different instruments with differing spectral resolutions and spectral interval centers. The SMARTS2 extraterrestrial spectra have been smoothed to a wavelength resolution corresponding to that of MODTRAN (2 cm^{-1}) and uniform spectral intervals mentioned above. The SMARTS2 and E490 spectra are in general agreement although the E490 spectrum has different spectral interval centers and resolution.

SMARTS2 incorporates ten widely used "reference" atmospheric profiles, including the USSA. The model accounts for Rayleigh, ozone, nitrogen dioxide, uniformly mixed gases, water vapor, and aerosol extinction properties, using individual parameterizations of the "optical mass" for each of ten constituent gases. Absorption functions are parameterizations of MODTRAN4 components, or derived from analysis of multiple MODTRAN4 model computations. Thus, SMARTS2 may be viewed as a "simplified" or "parameterized" MODTRAN4 model. The source code listing is about 4000 lines of FORTRAN code. The program provides much of the flexibility of MODTRAN with improved accuracy over the SPCTRL2 model. Because of the accuracy and ease of use of SMARTS2 with respect to MODTRAN, we selected it as the atmospheric transmission model to generate proposed revised spectral distribution standards.

We propose making an executable version of the SMARTS2 model available as an ASTM Adjunct Standard to the proposed revised standard spectral distribution standards. This would allow users to generate the standard spectra at will, as well as generate and investigate spectra under various non-standard conditions.

SMARTS2 Model Validation

As SMARTS2 consists of simpler parameterizations of the different MODTRAN4 submodels, extensive comparisons between MODTRAN and SMARTS2 model results have been performed. Comparisons of SMARTS 2.9 and MODTRAN4 differ at most by 5% in the ultraviolet region, as shown in Figure. 4. Because the latter outputs results in wavenumbers, rather than wavelengths, these results have been resampled and degraded to fit the SMARST2 resolution so that wavelength-by-wavelength comparisons can be performed.

Comparison with other rigorous atmospheric radiative models such as the spherical harmonics code of Braslau and Dave [51] and tabulations of Bird's results using the BRITE code [3] for the ASTM standard spectra [4, 5] have been performed and show excellent agreement [47].

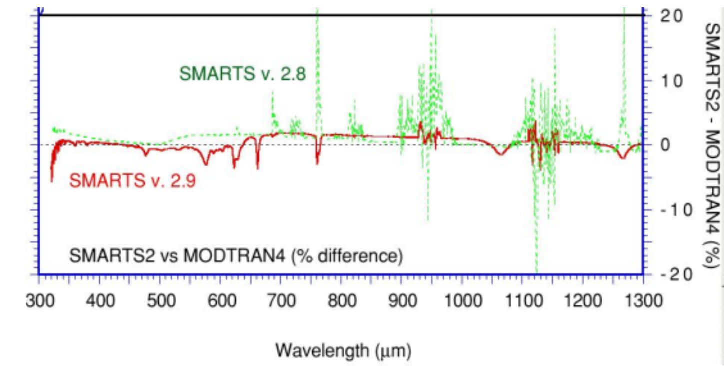

Figure 4. Percent Difference between atmospheric transmittance predicted by SMARTS2 Version 2.8 and 2.9 and MODTRAN4 for the same ASTM-E891 (G159 Direct Normal) conditions

Spectroradiometric data measured at FSEC and NREL were compared with SMARTS2 model results. The SMARTS2 predictions of both direct normal and global tilted irradiance are largely within the instrumental uncertainty (usually on the order of 5%) over spectroradiometer useful spectral range (400–1100 nm for the Li-Cor LI-1800 in this case, with a 6-nm FWHM). Figure 5 is an example of the numerous such comparisons with the Li-1800 instrument that have been performed.

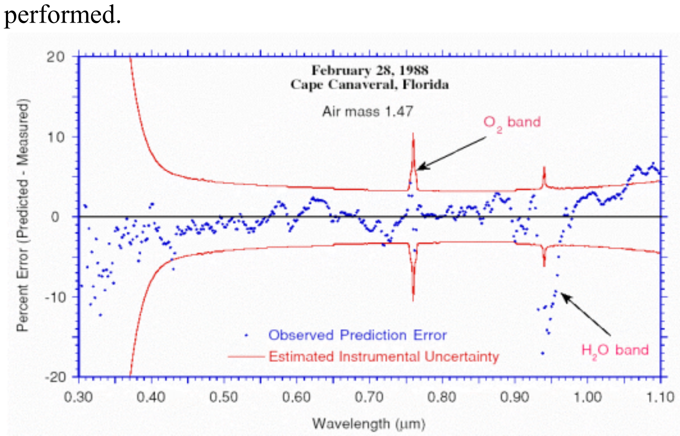

Figure 5. Percent difference between SMARTS2 modeled spectra and LI-1800 measured spectrum compared with Spectroradiometer measurement uncertainty envelope.

The percent difference between the modeled irradiance (direct normal or global tilted) always show a pattern of spectral deviations that probably result from mechanical or optical limitations in this single-monochromator instrument. The pattern of differences in Figure 5 repeats when using other units of the same model LI-1800 instrument. Similar comparisons with other types and brands of spectroradiometer show different patterns.

Direct normal spectra recorded at an air mass 1.5 ± 0.1 AM at FSEC over a period of two years have a substantially greater amplitude than the current standard direct normal spectra, even though the atmosphere in Florida can usually be regarded as "hazy". Tests conducted in Valencia, Spain with the same model Li-Cor instrument demonstrated SMARTS2 to be more accurate with respect the measured data than SPCTRL2.[44].

SMARTS2 model performance has been assessed in multiple comparisons with reference spectroradiometric data, with very good agreement over a variety of sun geometries and atmospheric conditions. Figure 6 compares modeled direct normal data with measurements made at NREL in Golden, Colorado, using a 5-nm-FWHM Spectroradiometer under three different air mass conditions. The model results (lines) have been smoothed with a 5 nm FWHM gaussian filter.

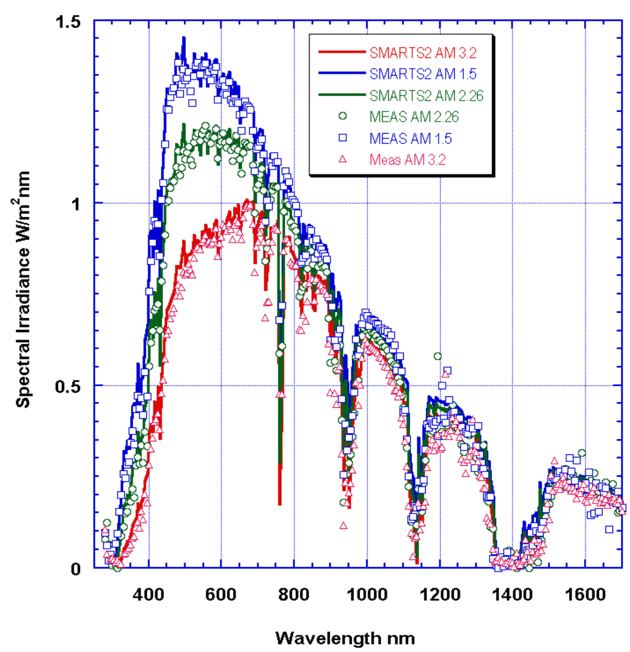

Figure 6. SMARTS2 results smoothed to 5 nm resolution (lines) and measurements (symbols) at 5 nm resolution for 3 different air mass conditions on a clear day at NREL Sep 28 2001

Osterwald and Emery have performed extensive implementation of the MODTRAN atmospheric transmission algorithms to extend measured spectra beyond 1100 nm [52]. The measured data is acquired using a Li-Cor model 1800 spectroradiometer with temperature-controlled detector. The Osterwald and Emery extension algorithm show excellent agreement (better than 0.8%) between measured broadband irradiances and the integrated spectral irradiances. These results validate the accuracy of the MODTRAN algorithms, and both directly and indirectly the SMARTS2 model parameterizations

PROPOSED REVISED SPECTRAL STANDARDS

A large number of direct and global spectra recorded at different U.S. sites have been analyzed to (i) validate the SMARTS2 radiative code under a variety of real atmospheric and environmental conditions and (ii) define appropriate conditions where PV power production and weathering and durability issues are important.

The criterion chosen was to examine data for sites in the NSRDB with at least 6 kWh/m^2/day annual direct normal irradiance. Table 3 lists the 15 sites meeting this criterion.

Table 3. NSRDB Site data for sites with annual daily mean DNI of at least 6 kWh/m^2/day

STATION	Direct Beam Kwh/m^2/day	AOD @ 500 nm	BB AOD
Daggett, CA	7.50	0.087	0.058
Las Vegas, NV	7.10	0.105	0.068
Tucson, AZ	7.00	0.099	0.065
Phoenix, AZ	6.80	0.142	0.090
Prescott, AZ	6.80	0.074	0.050
Alamosa, CO	6.80	0.029	0.024
Albuquerque, NM	6.70	0.074	0.050
Tonopah, NV	6.70	0.082	0.055
El Paso, TX	6.70	0.118	0.076
Flagstaff, AZ	6.40	0.074	0.050
Reno, NV	6.20	0.091	0.060
Cedar City, UT	6.20	0.074	0.050
Pueblo, CO	6.10	0.074	0.050
Tucumcari, NM	6.10	0.099	0.065
Ely, NV	6.00	0.050	0.036
Regional Avg.	<6.61>	<0.085>	<0.056>

The mean AOD at 500 nm for these sites is 0.085. We propose that the new revised spectra be based on the same atmospheric conditions specified for the present standards, except the AOD at 500 nm be specified as 0.084. This slight deviation is suggested since in conjunction with a specific realistic spectral albedo file (included with the SMARTS2 model) for “light soil”, rather than the artificial uniform albedo of 0.2 used in the current standard, the integrated values of the hemispherical tilted spectrum is 1000.37 W/m^2, or essentially the 1000 W/m^2 representing SRC for flat plate PV testing. The integral for the direct normal spectrum for these conditions is 900.14 W/m^2, or essentially 900 W/m^2. Figure 7 compares the resulting proposed spectra with the existing standard spectra.

We propose that the revised spectra are more realistic and representative conditions for the intended applications. The average percentage of reading difference between the proposed average tilted hemispherical spectrum and the historical hemispherical spectrum is only -0.05% in the region from 305 nm to 1100 nm, reducing the impact on the crystalline silicon flat plate PV community.

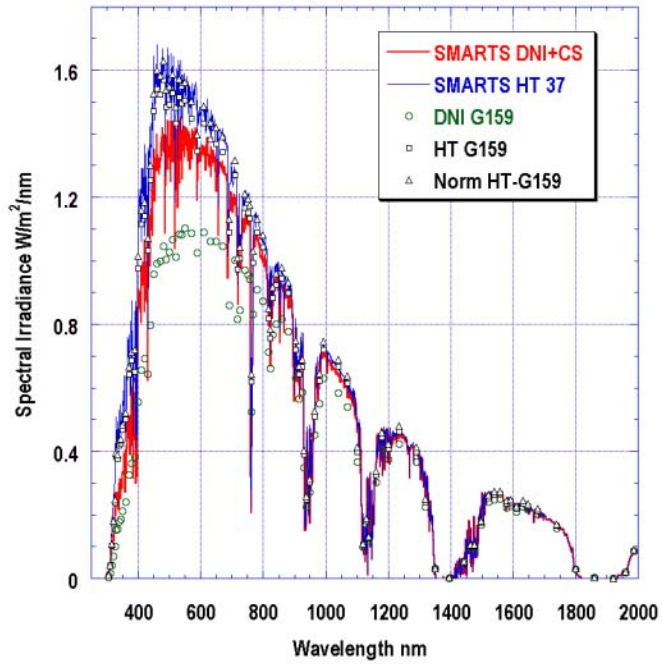

Figure 7. Present reference hemispherical tilt (HT), Normalized HT, and direct (DNI) ASTM G-159 standard spectra (symbols) compared with proposed SMARTS2 Ver. 2.9 modeled spectra (lines) for new reference condition AOD of 0.084 and light soil spectral albedo

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In 1982, the American Society for Testing and Materials (ASTM) adopted consensus standard direct-normal and global-tilted solar terrestrial spectra (ASTM E891/E892). These standard spectra were intended to evaluate photovoltaic (PV) device performance and other solar-related applications. The International Standards Organization (ISO) and International Electrotechnical Commission (IEC) adopted these spectra as spectral standards ISO 9845-1 and IEC 60904-3. Additional information and more accurately representative spectra are needed by today's PV community. Modern terrestrial spectral radiation models, knowledge of atmospheric physics, and measured radiometric quantities are applied to develop new reference spectra for consideration by ASTM.

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